UNCLASSIFIED

AD NUMBER
AD912102
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; JUL 1973. Other requests shall be referred to Naval Research Lab., Washington, DC 20390.**
AUTHORITY
USNRL ltr 30 Jan 1974

THIS PAGE IS UNCLASSIFIED

July 1973

AD912102

PULSED METAL VAPOR LASERS

PHASE II

QUARTERLY REPORT

T. W. Karras
R. S. Anderson
B. G. Bricks
W. E. Austin

Sponsored by
Defense Advanced Research Projects Agency
ARPA Order No. 2212

Space Sciences Laboratory
GENERAL ELECTRIC COMPANY
SPACE DIVISION
P.O. Box 8555
Philadelphia, Pennsylvania 19101

PULSED METAL VAPOR LASERS

PHASE II
QUARTERLY REPORT

ARPA Order No.:	2212, Amendment #1
Program Code:	3M10
Contract Effective Date:	August 1, 1972
Contract Expiration Date:	July 31, 1973
Amount of Contract:	$155,787
Contract Number:	N00014-73-C-0042
Principal Investigator:	Dr. Thomas W. Karras, (215) 962-4658
Scientific Officer:	Dr. J. R. Airey

This research was supported by the Defense Advanced Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-73-C-0042

Space Sciences Laboratory
GENERAL ELECTRIC COMPANY
SPACE DIVISION
P.O. Box 8555
Philadelphia, Pennsylvania 19101

I. SUMMARY

The principal effort of this phase of the program has been directed toward an attempt to demonstrate a bismuth vapor laser emitting at 4722 Å. This has involved some fundamental spectroscopic studies of bismuth and copper vapor discharges and a copper vapor laser. This goal has also required substantial effort directed toward developing a fast risetime discharge in the bismuth vapor and improving the operation of the bismuth vapor generator. Finally, work was also done to extend the operating time of the quenching spark gaps at high repetition rates and power levels for application to the metal vapor lasers.

II. OPTICAL TESTS

Many attempts at lasing the 4722 Å transition in bismuth were made during this period. Although none of these attempts have succeeded, an understanding of interfering mechanisms and possible solutions have been obtained. The following section will focus on these data with particular emphasis placed on "gain" measurements and spectroscopic studies of important transitions in atomic and diatomic bismuth. In assessing the relevance and accuracy of this data on bismuth, many parallel experiments were conducted in the copper vapor laser system. Hence much of this section also consists of a comparison between the two systems.

A. Development of the Laser Apparatus

In January 1973, a copper vapor laser was demonstrated at the General Electric Company's Space Sciences Laboratory. This laser was the first metal vapor laser to employ the copper vapor generator[1] developed at General Electric during the previous year. At the same time a similar generator for bismuth was developed on this program[2] with the ultimate objective of building a bismuth laser at 4722 Å in a system very similar to the above copper laser mentioned above. At the beginning of this phase of the program, the bismuth generator was assembled in the laser chamber and lasing action was sought with techniques similar to those used with copper.

It soon became clear that a program to improve electrical discharge characteristics was necessary. The objectives were twofold. Firstly, the current pulse had to have a faster risetime and shorter duration than had been necessary with copper. Secondly, the discharge had to be uniform over the 4 cm length if the gain of the system was to be maximized. To obtain the first objective, lower inductance circuitry had to be built.

The discharge used on the first copper laser and in early tests to lase bismuth employed a "T" electrode configuration. The "T" electrodes were made from molybdenum and entered the chamber from either side. The walls of the chamber were

electrically "floating" and the return path consisted of three braided cables running underneath the chamber. The energy storage elements were low inductance (2×10^{-9} h), high voltage (10 KV) capacitors ($1-7 \times 10^{-9}$ f), generally charged with 3-7 KV. Switching was accomplished with the quenching spark gaps developed during the first phase of this program. This configuration produced a 110 nsec risetime current pulse with a FWHM of also 110 nsec. A substantial percentage of the discharge occurred between either electrode and the chamber walls. Despite these inefficiencies, copper still lased at 5105 Å but copper at 5782 Å[1] would not. Similar attempts with bismuth also failed.

In the first major change, supported in part by this contract, the return path was shortened by running it inside the box thus greatly reducing the circuit inductance. To do this, however, it was necessary to use the chamber walls as part of the circuit. Since these walls were now no longer electrically "floating," most of the discharge went from the positive electrode to the wall. To overcome this, glass insulators were placed around the stem of the positive electrode and against the chamber walls. This proved very successful and the current pulse now had a risetime of 40 nsec and a FWHM of 60 nsec. Peak currents in the range 500-1000 amps were obtained but 200-500 amps were more generally used.

Although the electrical discharge now had a faster current pulse, the discharge was non-uniform since the molybdenum rods rapidly became pitted and developed a jagged edge. To rectify this, the "T's" were removed, and copper plate with razor blades fixed to the ends were installed.

This last electrical discharge configuration was an immense improvement when used in a copper vapor laser system[1]. Much lower copper densities were required to achieve threshold and at densities of 4×10^{14} atoms/cm^3, the system required only one mirror to lase. In addition lasing action at 5782 Å was observed using 87 percent and 47 percent transmitting mirrors. The specific laser energy in the laser cavity and the percentage of copper atoms which contribute to lasing action reached values above .055 j/ℓ and 33 percent. These numbers are a substantial improvement over what had been obtained previously.

B. Bismuth Lasing Efforts

The apparatus developed in Section A was used with bismuth, as the earlier system was, by making two substitutions. Mirrors with high reflectivities (99.99 percent and 99 percent) at 4722 Å were used in the cavity optical system and aligned by lasing copper in the apparatus. The copper vapor generator was then replaced by a bismuth vapor generator[2]. Densities of bismuth as high as 4×10^{16} were used in a variety of buffer gases (nitrogen, neon, helium, argon, and krypton) at various pressures. No lasing was observed, and at this time an optical system to measure gain and study the significant spectral lines in bismuth was assembled.

1. Gain Measurements

To make gain measurements the output mirror was removed and the monochrometer tuned to 4722 Å. The light at this wavelength comes from two different paths. The first is light originating in the laser chamber and passing directly to the monochrometer, while the second is light originating in the laser chamber, traveling to the rear mirror, reflecting off of it and traveling back through the laser chamber to the monochrometer. A thorough optical analysis considering all limiting apertures, mirror reflectivities and polarization effects of the Brewster windows indicate that this second source of light will be about 31 percent of the primary source for optically clear plasma. If absorption occurs it will be less than 31 percent while if gain occurs it will be more than 31 percent.

Using this system, changes as high as 36 percent were measured while monitoring the 4722 Å transition in bismuth with argon as a buffer gas. This indicates a real single pass gain of 5 percent in a 4 cm length discharge. In a fast pulse system 5 percent gain may not be enough to produce a laser since the photon density has only 20 to 30 passes in order to build up. Since the stimulation emission rate is proportional to the photon density, a very high single pass gain will be necessary for the photon density to reach a level where stimulated emission will dominate the spontaneous emission.

To ascertain what was the minimum gain necessary for lasing, the bismuth vapor generator was replaced by a copper vapor generator and the 5105 Å transition was lased. At threshold when the lasing was barely visible 37 percent change was recorded for single pass gain and steady lasing conditions corresponded to 39-40 percent change. This indicates that threshold with this optical cavity requires single gains of 6-10 percent. Consequently, the bismuth system at 4722 Å may be very close to lasing and minor improvements may be all that is necessary to succeed. In a later section, these improvements will be discussed.

2. Important Transitions in Bismuth

Figure 1 is an energy level diagram for bismuth showing all of the strong transitions. The lines at 2989 Å, 2993 Å, 2524 Å, and 2897 Å are very influential since they terminate in the lower state of the 4722 Å transition. If these lines are strong, they could populate the lower laser level, destroy any inversion and hence prevent lasing. Of these four transitions, the line at 2989 Å is most important since its upper state is directly connected to the ground state by direct electron excitation. That is, the upper state of the 2989 Å will be populated exactly as the upper state of the 4722 Å line is and its cross section for excitation should be comparable.

Only three of these lines were observed as our optical system did not pass light at 2524 Å. Figure 2 shows the results of these measurements. As can be seen on this figure, the 2989 Å is the strongest, but the 2993 Å line is nearly as strong and both of these lines together may be strong enough to destroy any inversion. Even more important, however, is the time sequence of events. The 2989 Å line and the 2993 Å line begin 10 nsec before the 4722 Å line appears in emission. Consequently the lower state is being populated before the upper state, making inversion extremely difficult. To counteract this, a faster discharge current pulse is required.

One other strong transition in bismuth is observed. This is the main resonant line at 3067 Å and a plot of its intensity relative to the 4722 Å line is also shown in Figure 2. The 4722 Å is more intense than the 3067 Å line indicating radiation trapping of the resonant line. Based upon spectroscopic data[3], one would expect

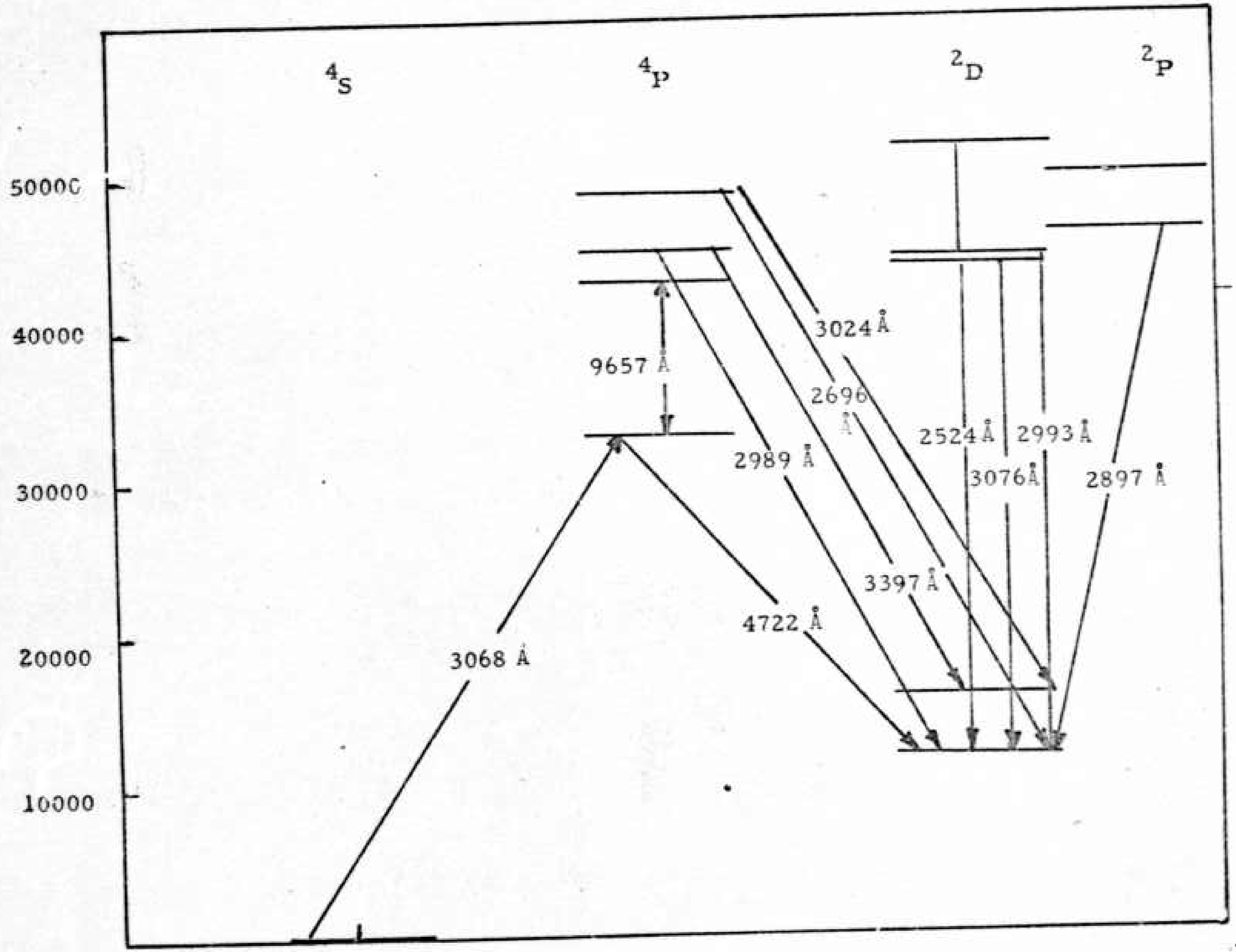

Figure 1. Bismuth Energy Level Diagram

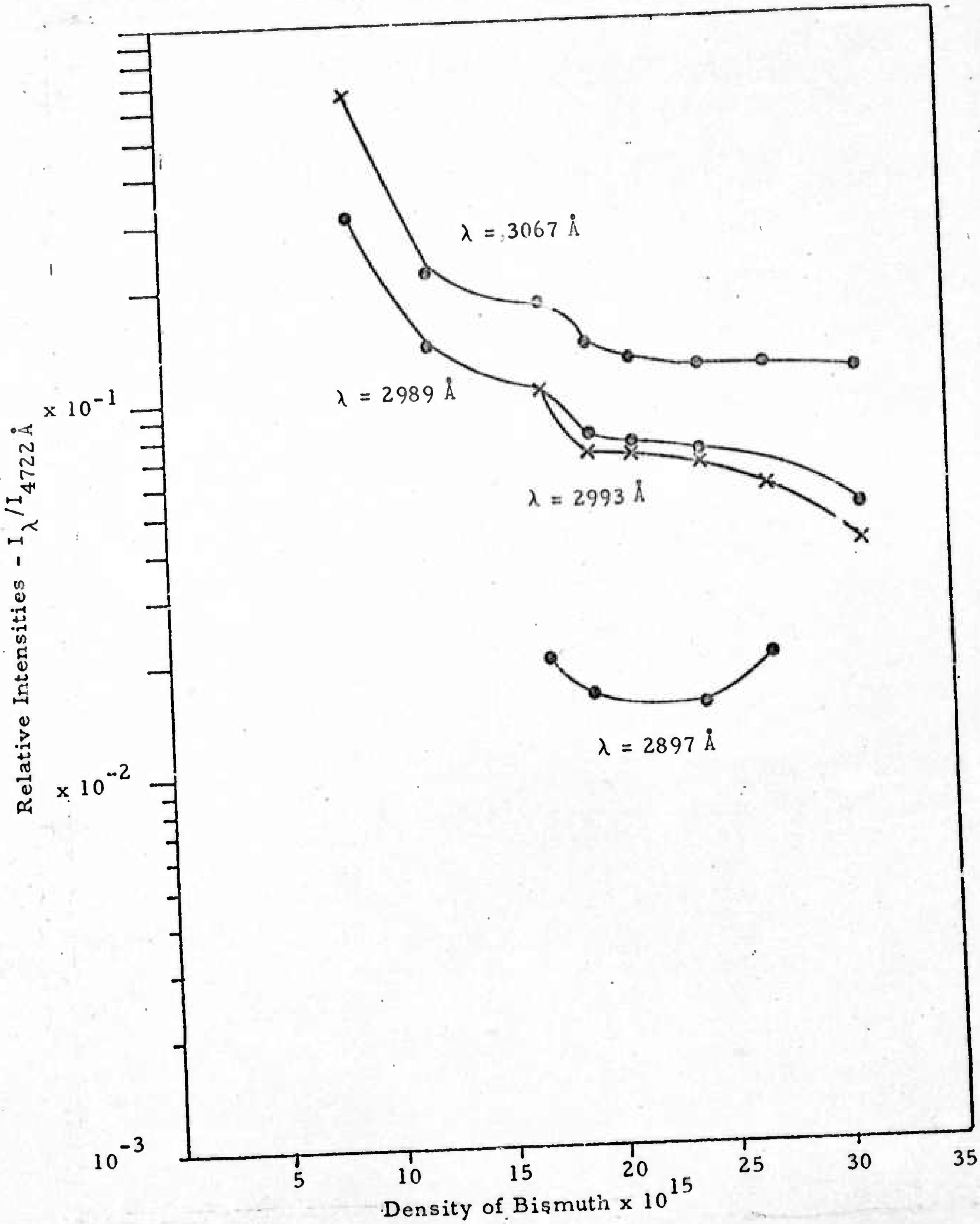

Figure 2. Bismuth Line Intensities

3067 Å line to be 60 times more intense than the 4722 Å line if no radiation trapping occurred.

3. Improvements

As mentioned above, the 2989 Å line appears 10 nsec prior to the appearance of the 4722 Å line. This may be merely a lifetime effect or it may be a pumping rate effect. In any event, this early appearance of the 2989 Å line signifies a populating of the lower laser state greatly inhibiting any inversion. To overcome this difficulty, the $^4P_{1/2}$ state (upper state of the 4722 Å line) must be populated faster than it currently is. This entails a much faster electrical discharge ultimately producing a 5-10 nsec risetime as opposed to the 40 nsec risetime pulse just described.

III. DISCHARGE TESTS

The requirement for extremely fast risetime discharge pulses, as noted in the previous section, had been pointed out previously[4]. As a result, studies as to how this result might be achieved were begun early in this phase of the program.

The electrical circuitry had several limitations placed upon it. The available capacitors and switches had inductances of 2 nh and 2.5 nh. Consequently, in the ideal circuit in which the load, electrodes, and other circuit elements had no inductance, the current risetime given by simple LRC circuit analysis is

$$\tau = \frac{1}{\omega_o} \tan^{-1} \frac{\omega_o}{\alpha} \qquad \alpha < \frac{1}{LC}$$

or

$$\frac{1}{\omega_o} \tanh^{-1} \frac{\omega_o}{\alpha} \qquad \alpha > \frac{1}{LC}$$

is the order of $2\text{-}6 \times 10^{-9}$ sec depending on circuit resistance. Any substantial increase of the circuit inductance above 4.5 nh would thus prevent the attainment of the risetimes needed (10-20 nsec, see Section II.B.3).

Since the inductance of the discharge could not be readily controlled, effort was concentrated upon reducing the inductance of the electrodes, vacuum feed-through, and the structure connecting them to the switch and capacitor. This problem was complicated by the fact that the circuit elements within the vacuum chamber would be exposed to relatively high temperatures and extraneous discharges had to be suppressed. The available laser chamber presented another limitation in that it only had 1-1/2" diameter ports for insertion of the circuitry.

A series of tests were first performed using low temperature materials. These showed that the low inductance required could be achieved by using a parallel plane transmission line structure. Insulators appropriately surrounding these planes could prevent the unwanted discharges.

High temperature insulators, adequate for the bismuth application, proved to be elusive, however. At this time pyrex, aluminum oxide sheet, a variety of ceramic cements, and some readily fusible glasses have all proved promising. Several usable configurations have resulted. A continuing effort is underway to obtain a long term solution.

The initial vacuum feedthrough design used a commercial low inductance component (Ceramseal Inc.). This was needed because of the 1-1/2 inch port limitation. The circuit built around this feedthrough and 1-1/2 inch port limitation had only limited success. It demonstrated 15-20 nsec risetime currents but extraneous discharges proved a continuing problem. Furthermore, the narrow 1-1/2 inch width insured that parts of the structure would be directly under the bismuth injector where they would quickly become unacceptably loaded with metal.

Recently, a new laser chamber constructed for another program, has become available[5]. This chamber allows insertion of 6 inch wide elements and so a special design vacuum feedthrough, compatible with a wider electrode structure has been built. The increase in width is expected to allow operation with a bismuth injector with negligible interception of bismuth flow. Preliminary testing has again demonstrated 15-20 nsec current risetime and 30 nsec FWHM. Tests with bismuth vapor are underway.

IV. BISMUTH VAPOR GENERATOR

Demonstration of a bismuth vapor generator was reported for the first phase of this program[2]. Work has continued to make this device reliable and capable of long term operation at high flow rates.

As a result several design improvements were accomplished. Reservoirs 1-1/2 inches in diameter and 1-1/2 inches high, holding more than 350 grams of bismuth, are now in use. Injector holes have also been reduced to .0075 inches in diameter.

This latter change was made because it was found that with .015 inch injector holes liquid bismuth leakage would occur above about 150 amps heating current (600 watts, 2×10^{16} bismuth atoms per cc in laser cavity). A large liquid bismuth head would cause leakage of liquid at lower input currents. Unfortunately, the use of smaller injector holes carries with it the penalty of a smaller open area because of manufacturing limitations (33 percent vs. 51 percent for the .015 inch hole injectors).

Another limitation has been circumvented by changes in the catcher placed below the bismuth vapor generator. As reported previously[2], as the bismuth flow density increased, the cooled catcher surface intended to catch the vapor performed its function inefficiently, resulting in a large backscattering and eventually nucleation. This produced large scattering losses and a visually observable effect upon the primary vapor stream. To avoid this an improved catcher has been designed and is currently being used. Instead of encountering a cooled flat plate the vapor stream now enters a cooled tube which is pumped at its other end. Backscattering and nucleation have been so reduced as to be no longer observable.

The bismuth vapor generator has thus been reduced to a simple reliable tool. Continuous flows with densities in the laser cavity of over 10^{15}/cc can be produced for hours without significant fluctuation. Reservoir capacity is the only limitation. No failures traceable to the generator itself have occurred.

V. QUENCHING SPARK GAP

Operation of the quenching spark gap at rates up to 250 KHz was demonstrated earlier[2]. Extended operation with sufficient energy pulses for laser operation, however, proved difficult. Sputtering and thermal effects soon caused failure.

A series of modifications were undertaken to solve these problems so that high repetition rate laser operation could be maintained for reasonable periods. The modifications thus far found to be most useful are an increase in electrode area and use of heavy refractory metals in the electrodes and screens.

The increase in electrode area from 1/4 inch to 1 inch in diameter led to a corresponding decrease in current density. This change, without having converted to refractory metal screens, allowed almost indefinite operation at 10^3 Hz (2.5×10^{-9} f, 3 KV, 11 watts). Failure did occur, however, after on hour's operation at 10^4 Hz.

Use of a paraffin oil bath extended this substantially. Fifteen minutes operation was thus maintained with almost 1.5 KW being dissipated. Examination of the failure mode (warping of the brass screens) shows that thermal effects are limiting. It is expected that once refractory metal and better cooling are used a great increase in lifetime should result.

Besides evaluation of the above changes in construction, a series of calorimetric measurements are being undertaken to establish what parameters will minimize the power dissipated within the spark gap.

VI. FUTURE PLANS

The primary effort of the remainder of this phase of the program will be directed toward attempts to make bismuth lase at 4722 Å. Use of fast rising discharge pulses and spectroscopic analysis will be emphasized. Evaluation of the effects of the bismuth dimer (whose presence in the vapor stream is in question because of the arguments given earlier and the absence of any strong emission bands) will also be considered.

Finally, a decision will be made as to whether bismuth or copper should be pursued in future laser development. There is serious doubt at this time whether a bismuth laser, even if it can be made to last at 4722 Å, will have any overall efficiciency advantage over a copper laser. The advantage in water transmissivity is likely to be overwhelmed by energy inefficiency due to excitation of unwanted atomic states and cascade population of the lower laser state. The excellent performance recently obtained with copper will be hard to surpass.

REFERENCES

1. T. W. Karras et al, "Copper Vapor Generator," Final Report to contract F29601-72-C-0079.

2. T. W. Karras and W. E. Austin, "High Repetition Rate Metal Vapor Lasers," Final Report to Phase I, Contract N00014-73-C-0042.

3. W. Meggers, C. Corliss, and B. Scribner, Tables of Spectral Intensities Pt. 1, NBS Monograph #32, 1961.

4. T. W. Karras and C. E. Anderson, "Proposal for Copper Vapor Generator," GE N11262, 1971.

5. R. S. Anderson, B. G. Bricks, and T. W. Karras, "Advanced Laser Technology," General Electric IR&D Task 73R262.